

Comparing galaxy populations in compact and loose groups of galaxies

Valeria Coenda, Hernán Muriel & Héctor J. Martínez

Instituto de Astronomía Teórica y Experimental (IATE), CONICET-Observatorio Astronómico, Universidad Nacional de Córdoba.
Laprida 854, Córdoba, X5000BGR. Argentina.
e-mail: vcoenda;hernan; julian@oac.uncor.edu

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ABSTRACT

Aims. We perform a comparison of the properties of galaxies in compact groups, loose groups and in the field to deepen our understanding of the physical mechanisms acting upon galaxy evolution in different environments.

Methods. We select samples of galaxies in compact groups identified by McConnachie et al., loose groups identified by Zandivarez & Martínez, and field galaxies from the Sloan Digital Sky Survey. We compare properties of the galaxy populations in these different environments: absolute magnitude, colour, size, surface brightness, stellar mass and concentration. We also study the fraction of red and early type galaxies, the luminosity function, the colour-luminosity and luminosity-size relations.

Results. The population of galaxies in compact groups differ from that of loose groups and the field. The fraction of red and early type galaxies is higher in compact groups. On average, galaxies in compact groups are systematically smaller, more concentrated and have higher surface brightness than galaxies in the field and in loose groups. For fixed absolute magnitude, or fixed surface brightness, galaxies in compact groups are smaller.

Conclusions. The physical mechanisms that transform galaxies into earlier types could be more effective within compact groups given the high densities and low velocity dispersion that characterise that particular environment, this could explain the large fraction of red and early type galaxies we found in compact groups. Galaxies inhabiting compact groups have undergone a major transformation compared to galaxies that inhabit loose groups.

Key words. Galaxies: groups: general – galaxies: fundamental parameters – galaxies: evolution

1. Introduction

Galaxies inhabit a wide range of environments, from isolated galaxies to the core of galaxy clusters and compact groups (hereafter CGs). There is clear evidence that both the properties of galaxies and the relative fraction of different type of galaxies depend on the environment (e.g. Oemler 1974; Dressler 1980; Goto et al. 2003; Blanton et al. 2005). In low density environments, galaxies tend to be blue, star forming and late-type, while dense environments are dominated by red, early-type galaxies. However, density is not the only relevant parameter when characterising the relationship between environment and galaxy properties, moreover, it is well known that galaxy properties strongly depend on stellar mass (e.g. Kauffmann et al. 2004). The dynamics of the system, e.g. the relative speed with which galaxies move, or the characteristics of the intergalactic medium, e.g. the presence of hot gas, may influence the evolution of galaxies and thus modify their properties. Within this scenario, different physical processes that can affect the evolutionary history of galaxies have been proposed. Galaxy-galaxy interactions, mergers or galaxy harassment can substantially change the structure of galaxies and even cause significant loss of mass (e.g. Toomre & Toomre 1972; Moore et al. 1998). On the other hand, the presence of gas in the intergalactic medium can substantially affect galaxies through mechanisms such as ram pressure (e.g. Gunn & Gott 1972; Abadi et al. 1999) or strangulation (e.g. Larson et al. 1980; Balogh et al. 2000; Kawata & Mulchaey 2008). The relative influence of these processes depend on several physical parameters which vary from

one environment to another, therefore comparative studies involving different galaxy environments are useful for a more complete understanding of their effect on galaxy evolution.

Among the various environments, CGs are an extreme case. Although their densities are among the highest observed, both, the number of members, and the velocity dispersion of galaxies are lower than those seen in massive loose groups or clusters of galaxies (Hickson et al. 1992). On the other hand, the number of galaxies and the velocity dispersion of CGs and low-mass loose groups may be comparable, although the crossing times are substantially different. These similarities and differences between loose groups (hereafter LGs) and CGs represent an useful scenario to test the influence that different physical processes have on the galaxy evolution. Moreover, Diaferio et al. (1994) suggested a tight connection between loose and compact groups. They estimated that the mean lifetime of a compact configuration is ~ 1 Gyr and suggested that on this time scale, members may merge and other galaxies in the loose group may join the compact configuration. While the properties of galaxies in CGs and LGs have been extensively studied separately, no systematic comparison using homogeneous and statistically significant samples have been performed so far. Lee et al. (2004) compared the properties of field and CGs galaxies and found that the colours of CGs galaxies differ from those of field galaxies in the sense that CGs have a higher fraction of elliptical galaxies. Deng et al. (2008) compared the properties of CGs, isolated, and field galaxies and found that, in dense regions, galaxies have preferentially greater concentration index and early-type morphology. There are numerous studies on the

star formation in CGs: Walker et al. (2010) suggest that the compact group environment accelerate the evolution of galaxies from star-forming to quiescent; Bitsakis et al. (2010) found a connection between dynamical state and the star formation rate (SFR) in the sense that old CGs host late-type galaxies with slightly lower specific star formation rate than in dynamically young groups; Johnson et al. (2007) also found a connection between the star formation and the global properties of groups. Tzanavaris et al. (2010) estimated the SFR using both ultraviolet and infrared information and found that the compact groups environment accelerate the galaxy evolution by enhancing the star formation processes and favouring a fast transition to quiescence.

The intra-group medium (IGM) in CGs has been extensively studied and can provide useful information on the evolution of galaxies. Torres-Flores et al. (2009) searched for young objects in the intra-group medium of several CGs and found that groups are in different stages of interaction. Many CGs show X-ray emission associated to the hot intra group medium (HIGM), Rasmussen et al. (2008) study the influence of the HIGM on the galaxy evolution and found that galaxy-HIGM interactions would not be the dominant mechanism driving cold gas out of the group members, been tidal interactions the most likely process to remove gas from galaxies in CGs.

Historically, the identification of CGs has been performed in projection, which causes the detection of spurious systems. While this can be solved with redshift determinations, the observed compact configuration could be the result of projection effects within LGs. These effects have been quantified by McConnachie et al. (2008), Díaz-Giménez & Mamon (2010) and Mendel et al. (2011). These studies showed the presence of contamination by chance association of galaxies in CGs. Brasseur et al. (2009) found that only 30 per cent of the simulated groups are truly compact in three dimensions. This contamination effect will bias any observational study. Even more radical is the scenario proposed by Tovmassian et al. (2006) who claim that CGs are not different from LGs. However, the general consensus is that a significant fraction of the compact groups with accordant-velocity members are physically dense systems. Hickson (1982) compiled a sample of 100 CGs based on the photographic plates of the Palomar Observatory Sky Survey. This sample has been extensively studied, however the low number of systems does not allow the implementation of statistical studies which could disentangle some dependencies between galaxy properties and environment. Based on surveys of galaxies, other samples of CGs have been identified (e.g. Iovino et al. 2003; Lee et al. 2004). Using the original selection criteria of Hickson (1982) and based on the Sixth Data Release of the Sloan Digital Sky Survey (DR6, Adelman-McCarthy et al. 2008), McConnachie et al. (2009) identified two samples of CGs, one of 2,297 compact groups down to a limiting magnitude of $r = 18$, and a deeper sample of 74,791 down to $r = 21$.

LGs have been extensively identified in large redshifts surveys such as the 2dFGRS (Colless et al. 2001) and SDSS (York et al. 2000), allowing the identification of thousands of loose groups in the nearby universe (e.g. Merchán & Zandivarez 2002, 2005; Eke et al. 2004; Yang et al. 2007). The dependence of galaxy properties on the group properties has been studied by several authors (e.g. Martínez et al. 2002; Weinmann et al. 2006; Martínez & Muriel 2006; Gerke et al. 2007; Hansen et al. 2009; McGee et al. 2011; Wetzel et al. 2011). Weinmann et al. (2009) investigated sizes, concentrations, colour gradients and surface brightness profiles of central and satellite galaxies in LG groups. These authors found that at fixed stellar mass, late-type satellite galaxies have smaller radii, larger concentrations, lower surface

brightness and redder colours than late-type central galaxies. This effect is not found for the early-type galaxies. Similar results are found by Maltby et al. (2010). Nair et al. (2010) found no environmental dependence in the size-luminosity relation for early-type galaxies. On the hand, several authors found a clear dependence of the size-luminosity relationship of early-type galaxies between central and satellite or field galaxies (e.g. Coenda & Muriel 2009; Bernardi 2009).

The purpose of this paper is the comparison between the properties of galaxies in compact groups and loose groups using homogeneous samples of galaxies and groups having similar spatial distributions.

This paper is organised as follows: in section 2 we describe the samples groups and galaxies we use in this paper; in section 3 we perform comparative studies of the galaxy populations in CGs, LGs and the field; in section 4 we compare some photometric scaling relations for galaxies in these environments. We summarise and discuss our results in section 5. Throughout this paper we assume a flat cosmological model with parameters $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$ and a Hubble's constant $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$. All magnitudes have been corrected for Galactic extinction using the maps by Schlegel et al. (1998) and are in the AB system. Absolute magnitudes and galaxy colours have been K -corrected using the method of Blanton et al. (2003) (KCORRECT version 4.1).

2. The samples

2.1. The sample of compact groups

The sample of CGs used in this paper has been drawn from the catalogue of CGs identified by McConnachie et al. (2009). This catalogue was identified in the public release of the SDSS DR6 (Adelman-McCarthy et al. 2008). McConnachie et al. (2009) used the original selection criteria of Hickson (1982), which defined a CG as a group of galaxies with projected properties such that: the number of galaxies within 3 magnitudes of the brightest galaxies is $N(\Delta m = 3) \geq 4$; the combined surface brightness of these galaxies is $\mu \leq 26.0 \text{ mag. arcsec}^{-2}$, where the total flux of the galaxies is averaged over the smallest circle which contains their geometric centres and has an angular diameter θ_G ; and $\theta_N \geq 3\theta_G$, where θ_N is the angular diameter of the largest concentric circle which contains no additional galaxies in this magnitude range or brighter.

McConnachie et al. (2009) identified 2,297 CGs, adding up to 9,713 galaxies down to a Petrosian (Petrosian 1976) limiting magnitude of $r = 18$ (Catalogue A), and 74,791 CGs (313,508 galaxies) down to a limiting magnitude of $r = 21$ (Catalogue B). According to the authors, contamination due to gross photometric errors has been removed from the Catalogue A through the visual inspection of all galaxy members, and they estimated it is present in the Catalogue B at a 14% level. The Catalogue A, which we use in this paper as a primary data source, has spectroscopic information for 4,131 galaxies (43% completeness). This catalogue includes groups that have a maximum line-of-sight velocity difference smaller than 1000 km s^{-1} only, to remove interlopers. The median redshift of the groups in this catalogue is $z_{\text{med}} = 0.09$. In this work we use a subsample of the Catalogue A of McConnachie et al. (2009), restricted to CGs in the redshift range $0.06 \leq z \leq 0.18$, which have spectroscopic redshift from at least one member galaxy, and also restricted our analyses to galaxy members with apparent magnitudes $14.5 \leq r \leq 17.77$, i.e., the range in which the Main Galaxy Sample (MGS; Strauss et al. 2002) is complete. After

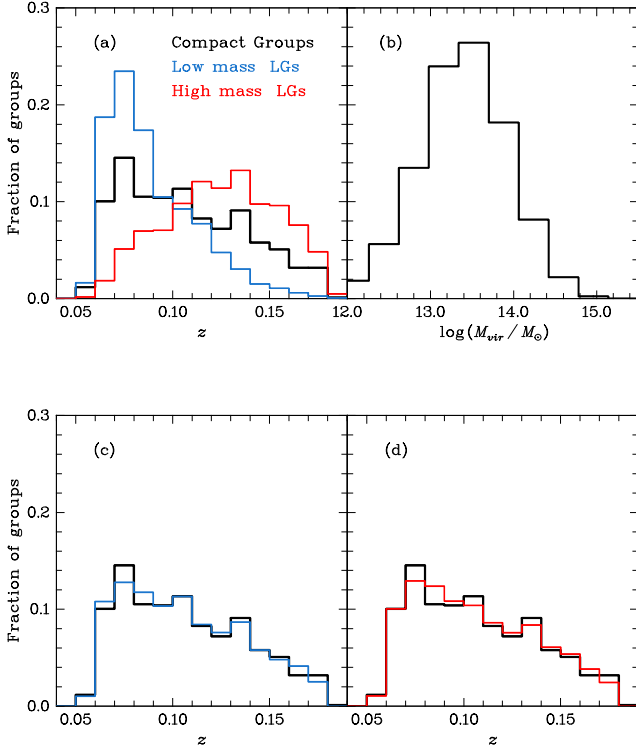


Fig. 1. Panel (a) shows the spectroscopic redshift distribution of our samples of CGs (black line), and LGs with $N_{gal} \leq 6$ in two ranges of virial mass: low-mass (blue line) and high-mass (red line). Panel (b) shows the virial mass distribution of LGs groups with $N_{gal} \leq 6$ and $0.06 \leq z \leq 0.18$. Panels (c) and (d) show the CGs redshift distribution (black line), and the low-mass (blue line) and high-mass (red line) subsamples of LGs restricted to have redshift distribution similar to that of the CGs by using a Monte Carlo algorithm (see text for details).

meeting all these conditions, our group sample comprises 846 CGs adding up to 2,270 galaxies, among which, 1,310 galaxies ($\sim 58\%$) have measured redshift. We show in the panel (a) of Fig. 1 the redshift distribution of the CGs in our sample. To every galaxy in the CGs with no redshift information we have assumed its redshift to be the parent group’s redshift.

2.2. The sample of loose groups

Loose groups of galaxies used in this paper are groups identified in redshift space, and are not required to fulfil any compactness or isolation criterion. In particular, we use groups drawn from the sample of Zandivarez & Martínez (2011) identified in the MGS of the Seventh Data Release (DR7, Abazajian et al. 2009). Briefly, they used a friends-of-friends algorithm (Huchra & Geller 1982) to link MGS galaxies into groups. This is followed by a second identification using a higher density contrast on groups which have at least 10 members, in order to split merged systems and clean up spurious member detection. Given the known sampling problems for bright galaxies, the group identification was carried out over all MGS galaxies with $14.5 \leq r \leq 17.77$. Group virial masses were computed as $M = \sigma^2 R_{vir} / G$, where R_{vir} is the virial radius of

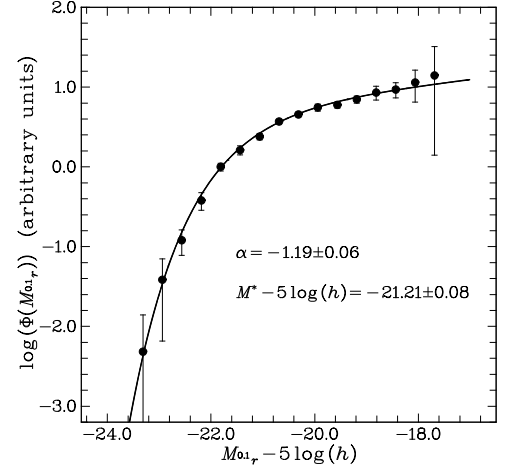


Fig. 2. The luminosity function of galaxies in Compact Groups. Continuous line is the best fit Schechter function with shape parameters quoted inside the figure. These parameters are used to compute the luminosities of CGs.

the system and σ is the velocity dispersion of member galaxies (Limber & Mathews 1960). The velocity dispersion was estimated using the line-of-sight velocity dispersion σ_v , $\sigma = \sqrt{3}\sigma_v$. The computation of σ_v was carried out by the methods described by Beers et al. (1990), applying the biweight estimator for groups with more than 15 member and the gapper estimator for poorer systems. The sample of Zandivarez & Martínez (2011) (hereafter ZM11) comprises 15,961 groups which have more than 4 members, adding up to 103,342 galaxies. Groups have a mean velocity dispersion of 193 km s^{-1} , a mean virial mass of $2.1 \times 10^{13} h^{-1} M_\odot$, and a mean virial radius of $0.9 h^{-1} \text{ Mpc}$. We refer the reader to ZM11 for details regarding the identification procedure and parameters.

2.2.1. The high and low mass subsamples

Since our work intends to perform a fair comparison between the galaxies inhabiting CGs and LGs we do not use the groups in the ZM11 sample in a straightforward way. It is well known that the properties of galaxies in groups are correlated with group mass (e.g. Martínez & Muriel 2006), thus, in our analyses below we compare galaxies in the CGs with galaxies in LGs in different mass ranges. We split groups in the ZM11 sample into 2 subsamples of low, $\log(M/M_\odot h^{-1}) \leq 13.2$, and high, $\log(M/M_\odot h^{-1}) \geq 13.6$, mass. These two subsamples have different redshift distributions, that also differ from that of the CGs, as can be seen in the panel (a) of Fig. 1. Thus a direct comparison of the galaxies in these 2 subsamples and in the CGs will certainly be biased. We then use a Monte Carlo algorithm to randomly select groups from these two subsamples in order to construct new subsamples of low and high mass LGs that have redshift distributions similar to that of the CGs. In panels (c) and (d) of Fig. 1 we show the resulting redshift distributions and the redshift distribution of the CGs as a comparison. A Kolmogorov-Smirnov test (KS) among any of those distributions and that of the CGs gives significance levels for the null hypothesis that they are drawn from the same distribution above 95%. Our final subsamples of low and high mass LGs include 2,536 and 2,529 systems, adding up to 8,749 and 10,055 galaxies, respectively.

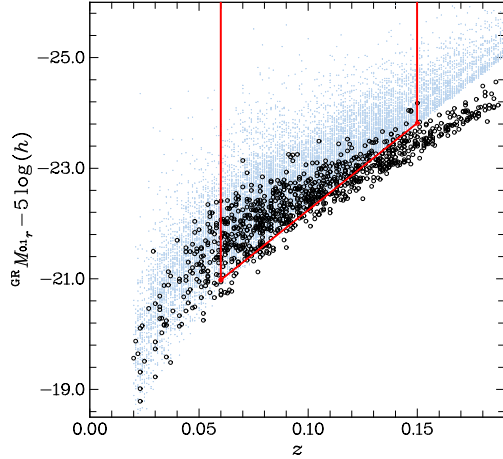


Fig. 3. The $^{0.1r}$ -band group absolute magnitude ($^{GR}M_{0.1r}$) as a function of redshift. Light blue dots are the LGs, open black circles are the CGs. We show in red lines the region of the diagram within which we select subsamples of LGs and CGs restricted to have similar redshift and absolute magnitude distributions.

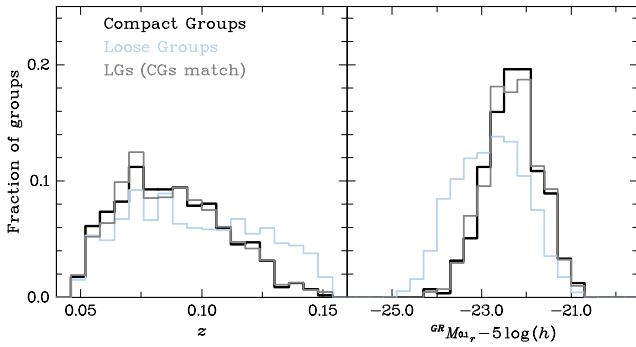


Fig. 4. Redshift (left panel) and total group absolute magnitude (right panel) distributions of groups in the region defined in Fig. 3: CGs (black), LGs (light blue) and LGs selected by a Monte Carlo algorithm in order to have similar redshift and absolute magnitude distributions as the CGs (grey).

2.2.2. The equal luminosity subsamples of compact and loose groups

Ideally, we would like to compare galaxies in LGs and CGs of similar masses, this can not be done since CGs in the McConnachie et al. (2009) catalogues do not have measured mass. Another way of comparing CGs and LGs that have similar characteristics can be done by selecting them according to the total luminosity of their galaxy members. Thus, we also perform a comparison of galaxy properties in samples of CGs and LGs with similar luminosity distributions. The luminosities of our LGs were computed by Martínez & Zandivarez (2012) by using the method of Moore et al. (1993), which accounts for the galaxy members not observed due to the apparent magnitude limit by means of the luminosity function (LF) of galaxies in groups. Martínez & Zandivarez (2012) used the mass dependent LF of ZM11.

To compute the total luminosities of the CGs using the method of Moore et al. (1993), we need first to compute the

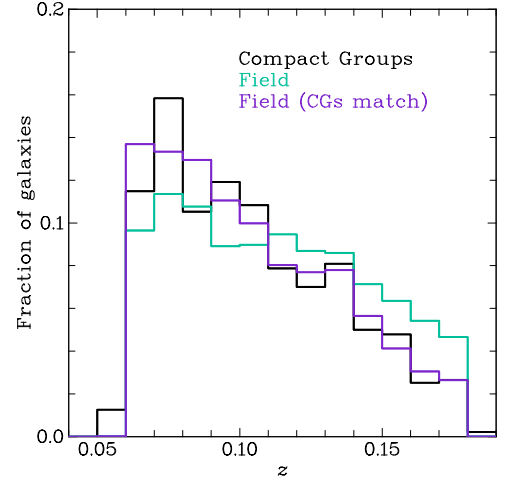


Fig. 5. Redshift distributions of galaxies: CGs sample (black), field galaxies (green) and field galaxies Monte Carlo selected to have a similar redshift distribution as CGs (violet).

LF of the galaxies in CGs. We use two methods to compute the LF of galaxies in CGs: the non-parametric C^- (Lynden-Bell 1971; Choloniewski 1987) for the binned LF and the STY method (Sandage et al. 1979) to compute the best fit Schechter (1976) function parameters. Since the Catalogue A of McConnachie et al. (2009) is complete down to an apparent magnitude $r = 18$ we included all galaxies brighter than this limit in the LF computation. We show in Fig. 2 the resulting LF of galaxies in CGs in the $^{0.1r}$ -band. The best fitting Schechter function has shape parameters $\alpha = -1.19 \pm 0.06$ and $M^* - 5 \log(h) = -21.21 \pm 0.08$ and clearly, is a good fit to the C^- points. It is interesting to compare this LF parameters with those found by ZM11 for the catalogue of LGs used in this paper. On one hand, the M^* is comparable with the value -21.18 ± 0.04 that ZM11 found for their highest mass bin, that is, groups with masses in the range $1.5 - 3.0 \times 10^{14} M_\odot h^{-1}$. On the other hand, the faint end slope value is consistent with the value -1.19 ± 0.04 corresponding to LGs of intermediate mass $\sim 3.5 \times 10^{13} M_\odot h^{-1}$ in ZM11.

We show in Fig. 3 the absolute magnitude of LGs and CGs as a function of redshift. Clear differences are observed between LGs and CGs: at a fixed redshift the brightest objects are LGs and the faintest are CGs. Among the LGs there are systems which can have more members than the typical CG and thus are brighter. CGs were identified over a parent catalogue which has a fainter apparent magnitude limit ($r = 18$) than the MGS ($r = 17.77$), which is the parent catalogue for the LGs of ZM11. This explains why there are CGs much fainter than even the faintest LGs, particularly at $z > 0.15$.

To perform a fair comparison between LGs and CGs having similar absolute magnitude distributions we firstly define a region in the redshift-absolute magnitude plane in which we can find both types of groups. As discussed above, for all redshifts $z > 0.05$, the CG sample includes systems which are fainter than all the LGs due to differences in the apparent magnitude limit of the parent catalogues. As can be seen in Figure 3 beyond $z > 0.15$ the samples of LGs and CGs do not overlap at all, this imposes the upper redshift cut-off. For the lower redshift cut-off we use the same value, $z = 0.06$, as in the other samples

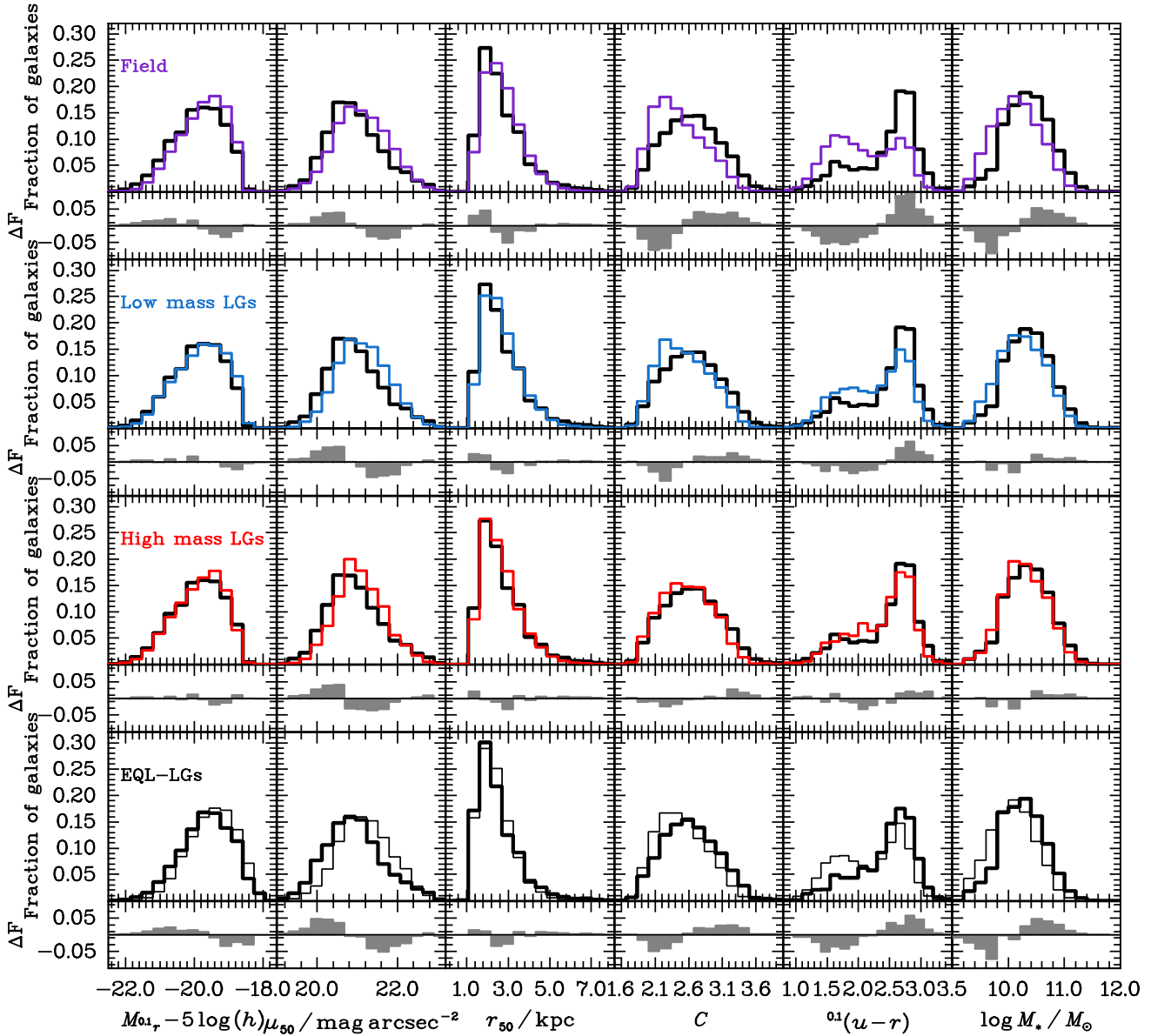


Fig. 6. Distributions of galaxy properties in our samples: CGs sample (*thick black line*), field (*violet*), low-mass LGs (*blue*), high-mass LGs (*red*) and EQL-LG (*thin black line*). All distributions have been normalised to have the same area. Below each panel we show as *shaded histograms* the residuals between the distributions.

defined before. Within this redshift range, we avoid the region in which only CGs are found, that is, we impose a redshift dependent faint absolute magnitude cut-off which, for simplicity, we have chosen to be linear. We indicate this region with *red lines* in Fig. 3. Now, within this region, LGs and CGs still have different redshift and absolute magnitude distributions which we show in Fig. 4 as *black* and *light blue* histograms respectively. We then select by means of a Monte Carlo algorithm, a subsample of LGs that match the redshift and absolute magnitude distributions of the CGs. This is shown as *grey* histograms in Fig. 4. When we compare LGs and CGs of equal luminosity in the

analyses below, we refer to these two subsamples of groups. Our final subsamples of EQL-CGs and EQL-LGs include 571 and 2,345 systems, adding up to 1,729 and 10,554 galaxies, respectively. We explicitly make this distinction between the CG and the EQL-CG samples since the latter has a redshift dependent absolute magnitude constraint that is absent in the former.

2.3. The sample of field galaxies

In this work we also compare the properties of galaxies in CGs with the properties of field galaxies. We consider as field galax-

ies to all DR7 MGS galaxies that were not identified as belonging to LGs by ZM11 groups or to CGs by McConnachie et al. (2009), and have apparent magnitudes $14.5 \leq r \leq 17.77$. For an adequate comparison with our samples of galaxies in groups, we used the same Monte Carlo algorithm of the previous subsection to contract a sample of field galaxies that has a similar redshift distribution as that of galaxies in our CG sample. This field sample includes 250,725 galaxies. We show in Fig. 5 the redshift distributions of galaxies in CGs, of all field galaxies and of field galaxies Monte Carlo selected. A KS test between the galaxies in CGs and in our Monte Carlo selected field samples gives significance levels for the null hypothesis that they are drawn from the same distribution above 95%. From now on, when we refer to field galaxies we mean galaxies in this Monte Carlo selected sample.

3. Comparing galaxies in CGs, LGs and in the field

In this section we compare parameters of galaxies in CGs, LGs and in the field. The parameters we have focused our study on are:

- Petrosian absolute magnitude in the $^{0.1}r$ -band;
- The radius that encloses 50% of the Petrosian flux r_{50} ;
- The r -band surface brightness, μ_{50} , computed inside r_{50} ;
- The concentration index, defined as the ratio of the radii enclosing 90 and 50 percent of the Petrosian flux, $C = r_{90}/r_{50}$;
- The $^{0.1}(u-r)$ colour. We use model instead of Petrosian magnitudes to compute colours since aperture photometry may include non-negligible Poisson and background subtraction uncertainties in the u band;
- The stellar mass, M_* based on luminosity and colour, computed following Taylor et al. (2011).

In the analyses below, we classify galaxies into early and late types according to their concentration index. Typically, early-type galaxies have $C > 2.5$, while for late-types $C < 2.5$ (Strateva et al. 2001). The effects of seeing in the measurement of r_{50} and r_{90} have to be considered for galaxies with relatively small angular size. The average seeing in the SDSS is below a conservative value of $1.5''$ (Shen et al. 2003). Since the values of r_{50} , μ_{50} and C can be unreliable for galaxies with r_{50} below this value, we have excluded them from our analyses. The numbers of galaxies in each sample quoted in the previous section already contemplate this size cut-off.

Since many galaxy properties correlate with absolute magnitude, thus, to perform a fair comparison we weight each galaxy in our computations by $1/V_{max}$ (Schmidt 1968) in order to compensate for the fact that we are dealing with galaxy samples that are drawn from flux-limited catalogues. Fig. 6 compares the normalised distributions of galaxy parameters of galaxies in LGs and in the field with those of CGs galaxies. Below each panel of Fig. 6 we show the residuals between each pair of distributions, i.e., for each property X , the difference $\Delta F(X) = f_{CG}(X) - f(X)$, where $f_{CG}(X)$ and $f(X)$ are the fractions of galaxies in the bin centred on X in the CGs and in the other sample, respectively.

Regarding the luminosity, and as can be seen from Fig. 6, galaxies in CGs tend to be slightly more luminous than their field counterparts, in the sense of an excess of $M_{0.1r} - 5 \log(h) \lesssim -20$ galaxies, this is in agreement with previous findings such as Deng et al. (2008). We find no clear difference with either low, and high mass LGs. A similar result is found by Deng et al. (2007) when comparing galaxies in CGs and LGs identified by different algorithms. Important differences can be seen between

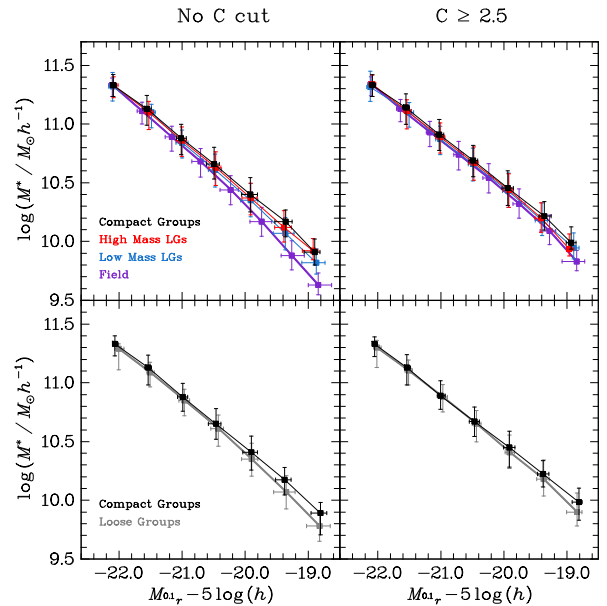


Fig. 7. The stellar mass as a function absolute magnitude for galaxies in our samples. Points represent the median in each bin, error-bars are the 25 and 75% percentile within each bin.

CGs and the sample of LGs restricted to have similar total luminosity distribution (hereafter EQL-LG): galaxies in CGs are systematically brighter.

Compared to all LG samples and the field, CGs have a larger fraction of galaxies with $\mu_{50} \lesssim 20.4 \text{ mag arcsec}^{-2}$ and a deficit of lower surface brightness galaxies.

When comparing galaxy sizes, we find differences between CGs and the other environments for galaxies with $r_{50} \lesssim 3 \text{ kpc}$. CGs have an excess of galaxies with $r_{50} \lesssim 2 \text{ kpc}$ and a deficit of $2 \text{ kpc} \lesssim r_{50} \lesssim 3 \text{ kpc}$ galaxies. Deng et al. (2008) do not find significant differences in the sizes of galaxies in CGs and a sample of field galaxies, which they argue it is due to their narrow luminosity range.

Galaxies in CGs are systematically more concentrated than their counterparts in the field or in LGs. This difference mirrors the fact that galaxies in CGs have, on average, smaller sizes and not very different luminosities than galaxies in the other samples. Thus, CGs have a higher fraction of early-type galaxies. In agreement with our results, Deng et al. (2008) find that CGs have a larger fraction of high concentrated early-type galaxies when compared to field galaxies.

In agreement with the excess of early type galaxies, galaxies in CGs show a higher fraction of red galaxies, compared to the field and the LGs. Our results agree with the comparison of CGs and field galaxies by Lee et al. (2004) and Deng et al. (2008). Brasseur et al. (2009) find similar results performing a similar comparison using mock catalogues based upon the Millennium Run simulation (Springel et al. 2005).

Galaxies in CGs tend to have larger stellar masses than their field and EQL-LGs counterparts. We further explore this in Fig. 7, where we show the median stellar mass as a function of absolute magnitude for galaxies in all our samples. Differences arise at the lower luminosities we explore, galaxies in groups differ from field galaxies, being more massive at fixed luminosity. At the same time something similar is observed when comparing the equal luminosity subsamples: there is a hint for galaxies in

CGs to be more massive at lower luminosities. All these differences are almost erased when we consider early types only.

As a general conclusion from this section, galaxies in CGs differ from galaxies in other environments. Differences are larger when compared to field galaxies and smaller when compared to galaxies in high mass LGs.

3.1. The fraction of red and early type galaxies in groups

As a complementary study, we also study the fraction of galaxies that are in the red sequence or are classified as early type as a function of galaxy absolute magnitude in the environments we probe. To quantify the fraction of red galaxies, we follow ZM11 and classify galaxies as red/blue accordingly to whether their $^{0.1}(u-r)$ colour is larger/smaller than the luminosity dependent threshold $T(x) = -0.02x^2 - 0.15x + 2.46$, where $x = M_{0.1r} - 5 \log(h) + 20$. To classify galaxies into early and late, we use the concentration parameter and consider as early types those galaxies which have $C > 2.5$.

Fig. 8 shows the fraction of red galaxies (*left panels*), early type galaxies (*centre panels*) and red early-types galaxies (*right panels*) as a function of galaxy absolute magnitude. The comparison among CGs, LGs samples and the field shows that CGs have a larger fraction of red early-type galaxies over the whole absolute magnitude range. For brighter luminosities, CGs and high mass LGs have similar fraction of red galaxies, the largest difference is observed when red and early-types galaxies are considered. Important differences can be seen between CGs and LGs of similar luminosities (*lower panels*).

4. Photometric relations

There are well known scaling relations involving photometric, structural and dynamical parameters of galaxies. Among the scaling relations that involve photometric parameters are the colour-magnitude (Sandage & Visvanathan 1978a,b), also known as the red sequence (RS) for early-type galaxies, and the luminosity-size relation. These empirical relations are closely related to the physical processes involved in the galaxy formation scenario and, therefore, are a fundamental tool to understand the formation and evolution of galaxies. In this section, we compare these relations for our samples of galaxies in CGs, LGs and in the field. As in the previous section we weight each galaxy by $1/V_{max}$ according to its absolute magnitude and the redshift and apparent magnitude cut-offs.

4.1. Colour-magnitude diagram: red sequence

Fig. 9 shows the colour-magnitude diagram as a function of environment. As expected, it is clear from the *left panels* of Fig. 9, that, as we move from field to LGs of increasing mass, the blue population declines in numbers, while red galaxies become the dominant population. For CGs the red population is even more dominant. The *right panels* of Fig. 9 consider only early-type galaxies, this does not completely remove a blue population which also becomes less prominent as we move from field to CGs. Lee et al. (2004) and Brasseur et al. (2009) found that galaxies in compact associations are confined nearly exclusively to the red sequence, with few galaxies occupying the blue cloud, in agreement with our results.

It is well known that, for a fixed absolute magnitude, M , the colour distribution of the galaxies is well described by the sum of two Gaussian functions representing the blue cloud and

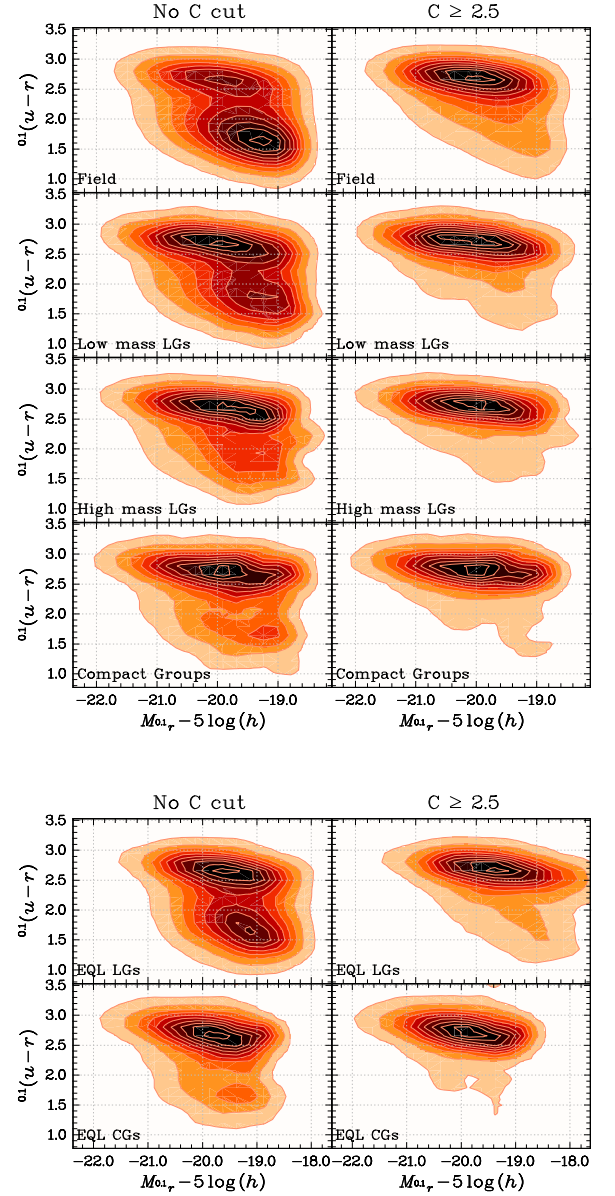


Fig. 9. Colour-magnitude diagram: $^{0.1}(u-r)$ as a function of $M_{0.1r}$ for galaxies in the field, in low and high mass LGs, and in CGs. Equal luminosity samples of CGs and LGs are shown separately. *Left panels* include all galaxies in the samples, while *right panels* include only early-type galaxies according to their concentration parameter. *Darker colours* represent higher values. All distributions have been normalised to enclose the same volume.

the red sequence (e.g. Baldry et al. 2004; Balogh et al. 2004; Martínez et al. 2006):

$$f(col|M) = A_B \exp\left(-\frac{(col - \mu_B)^2}{2\sigma_B^2}\right) + A_R \exp\left(-\frac{(col - \mu_R)^2}{2\sigma_R^2}\right). \quad (1)$$

In the equation above, A_B and A_R are the amplitudes, μ_B and μ_R the centres, σ_B and σ_R the width of the Gaussian functions describing the blue (B) and red (R) populations. We study the environmental dependence of the red sequence following the same procedure as in Martínez et al. (2010): for different abso-

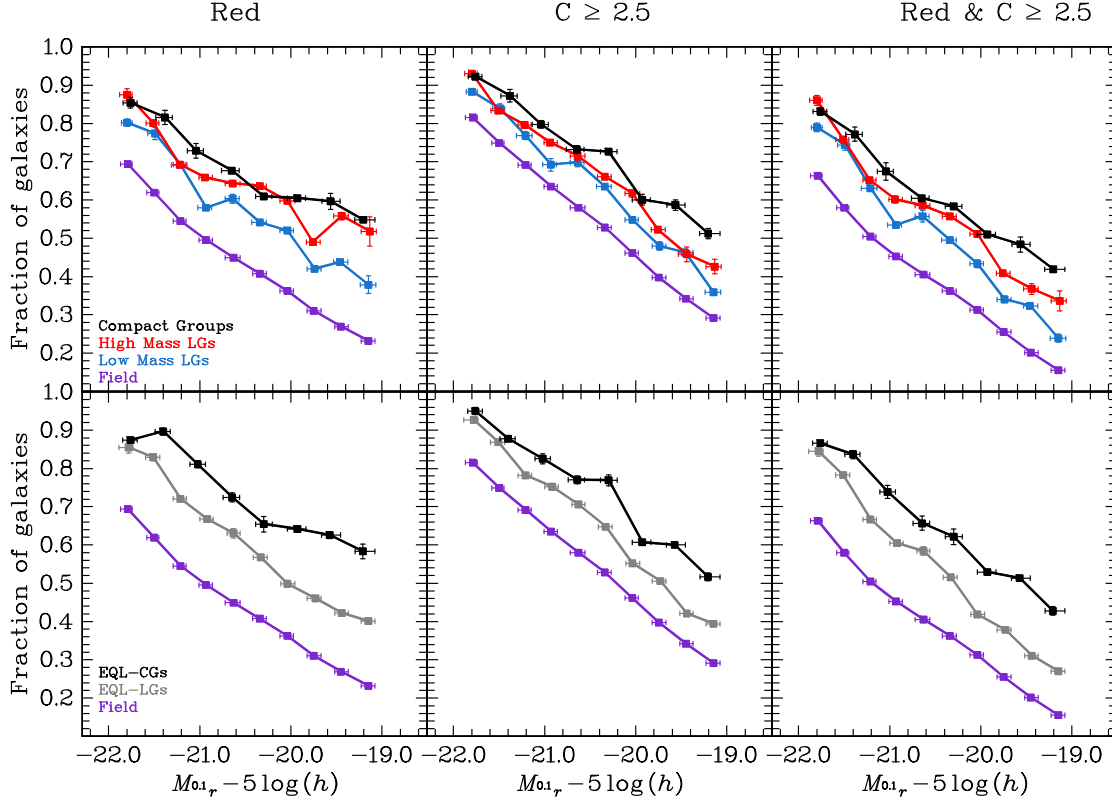


Fig. 8. *Left panels:* the fraction of red galaxies according to their $^{0.1}(u-r)$ colour; *centre panels:* the fraction of early-type galaxies according to their concentration parameter; *right panels:* the fraction of red early-type galaxies. All fractions are shown as a function of absolute magnitude. The *upper panels* compare CGs, LGs of low and high mass and field galaxies, while *lower panels* compare CGs and LGs with similar redshift and total absolute magnitude. Vertical error-bars are obtained by using the bootstrap resampling technique, horizontal error-bars are the 25 & 75% quartiles of the absolute magnitude distribution within each bin.

lute magnitude bins, we fit the two Gaussian model (Eq. 1) to the $^{0.1}(u-r)$ colour distribution of field, LG and CG galaxies, using a standard Levenberg-Marquardt method. Thus, for all our galaxy samples we have the 6 parameters of Eq. 1 as a function of $^{0.1}r$ -band absolute magnitude. In Fig. 10 we show the centre of the Gaussian function (μ_R) that fits best the red sequence in the colour-magnitude diagrams of Fig. 9. The abscissas are the medians of the corresponding distributions of the absolute magnitudes in each bin and the horizontal error bars are the 25 and 75 % quartiles.

In the absolute magnitude range we probe in this work, we find that data points in Fig. 10 are well described by a quadratic polynomial (Martínez et al. 2010). The continuous lines in figure 10 show the best quadratic fits to μ_R as a function of the absolute magnitude. This figure shows (*upper left panel*) that the red sequence of field galaxies is always bluer than its counterparts in groups. Among groups, the mean colour of the red sequence is systematically redder for the high mass subsample (as in Martínez et al. 2010). The μ_R of CG galaxies is, consistent with that of galaxies in high mass LGs over the whole range of absolute magnitudes we probe. When considering the samples of CGs and LGs of similar luminosities (*lower left panel*), μ_R of CGs is systematically redder for $M_{0.1r} - 5 \log(h) < -20.5$. When we consider red early-type galaxies alone (*right panels* of Fig. 10), the differences between field, LGs and CGs dis-

appear. Nevertheless, differences between the red sequences of CGs, LGs and the field are still present.

4.2. Luminosity-size relation

Fig. 11 shows the Petrosian half-light radius as a function of absolute magnitude of late (*lefts panels*) and early-type galaxies (*right panels*). As it is expected, brighter galaxies are larger, as has been found in several environments and regardless morphological types (e.g. Coenda et al. 2005; Bernardi et al. 2007; von der Linden et al. 2007; Coenda & Muriel 2009; Nair et al. 2010).

To analyse the luminosity-size relation, for each panel in Fig. 11 we derive the size distribution within several absolute magnitude bins. In all cases, for a fixed absolute magnitude, M , the size (r_{50}) distribution can be well described by a log-normal distribution (Shen et al. 2003), which is characterised by a median ($\mu = \ln(r_{\text{med}})$) and a dispersion (σ)

$$f(r_{50}|M) = \frac{1}{r_{50}\sigma\sqrt{2\pi}} \exp\left(-\frac{\ln(r_{50}) - \mu}{2\sigma^2}\right). \quad (2)$$

We fit this model to the distributions shown in Fig. 11 using a standard Levenberg-Marquardt procedure. Fig. 12 shows the median $\log(r_{\text{med}})$ as a function of absolute magnitude of the distributions shown in Fig. 11. For all samples of galaxies analysed

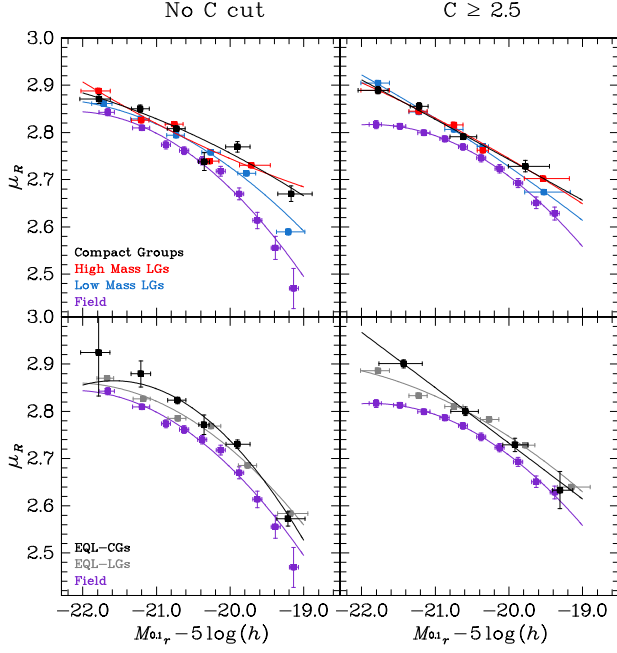


Fig. 10. μ_R of the sequences of red galaxies from Fig. 9 as a function of absolute magnitude. The abscissas are the median and the horizontal error bars are the 25 and 75 % quartiles of the absolute magnitude distribution within each luminosity bin. Vertical error bars are the 1σ error estimates from the fitting procedure. Continuous lines are the best-fitting quadratic models.

here, a quadratic polynomial function is a good description of the median $\log(r_{\text{med}})$ as a function of absolute magnitude. We also show these fits in Fig. 12. The curvature in the luminosity-size relation has been previously reported by Bernardi et al. (2007) and Coenda & Muriel (2009).

Taking into account error-bars, the differences among the different sequences in Fig. 12 are not significant for most of the bins. The only clear difference is seen between early-type galaxies populating the EQL CG sample and the field. Nevertheless, a systematic behaviour can be seen in all panels of Fig. 12: over the whole range on luminosities, galaxies in CGs tend to be the smallest, while field galaxies are the largest ones. This effect is observed for both, early and late-type galaxies. Weinmann et al. (2009) analysing central and satellite galaxies found a similar dependence of the size-luminosity relation with the environment, nevertheless, the effect is only observed for late-type galaxies. These authors adopted a more restrictive $C > 3$ value to select early-type galaxies. This threshold preferentially selects elliptical galaxies. In order to compare our results with those obtained by Weinmann et al. (2009) we have considered a sub-sample of early-type galaxies assuming a $C > 3$. The corresponding results are shown in the inset-panels of Figure 12, where it can be observed that the size-luminosity relation for $C > 3$ galaxies is the same for all the environments considered. This is also in agreement with Nair et al. (2010) who, by using a sample of visually classified bright sample of galaxies, found no dependence with environment of the size-luminosity relation for elliptical galaxies.

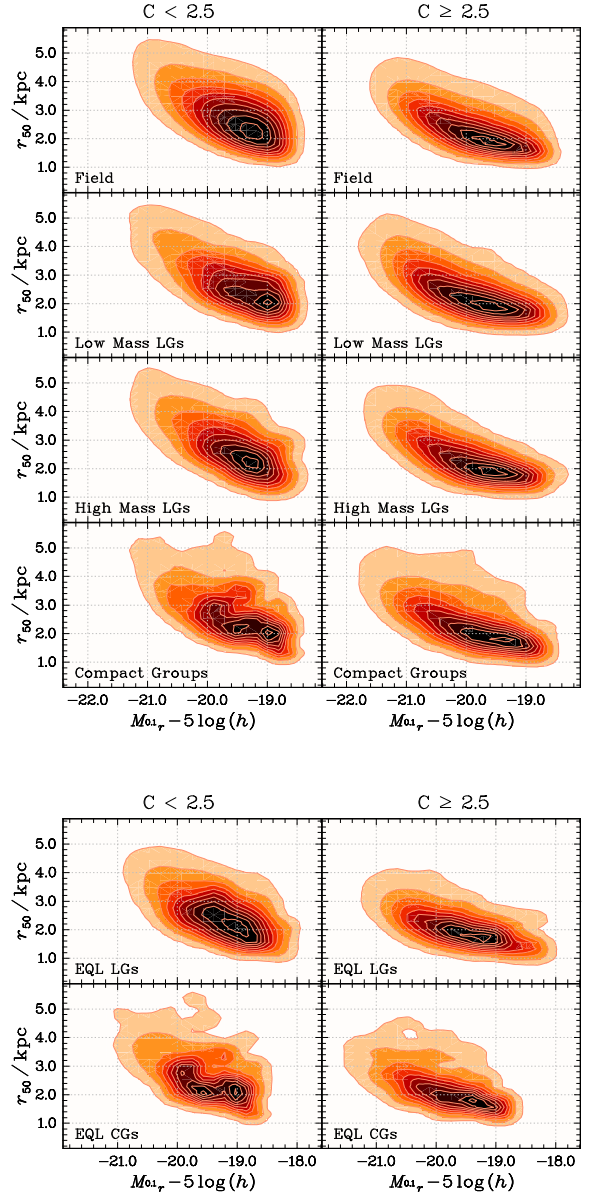


Fig. 11. Petrosian half-light radius, r_{50} , as function of the absolute magnitude for field, low and high mass LG and CG galaxies. Equal luminosity samples of CGs and LGs are shown separately. *Left panels* show late-type galaxies, while *right panels* consider early-type galaxies according to their concentration parameter.

5. Conclusions and Discussion

To investigate the dependence of the galaxy properties on environment, we performed a comparative study of the properties of galaxies in CGs, LGs and in the field in the redshift range $0.06 < z < 0.18$. CGs used in this paper were drawn from the Catalogue A of McConnachie et al. (2009), while LGs were selected from the sample of ZM11. In all cases, galaxy properties used in our work were taken from the MGS sample of the SDSS DR7.

We selected three samples of LG taken from the ZM11 catalogue: low ($\log(M/M_\odot h^{-1}) \leq 13.2$) and high ($\log(M/M_\odot h^{-1}) \geq 13.6$) mass. The third sample was selected in order to have simi-

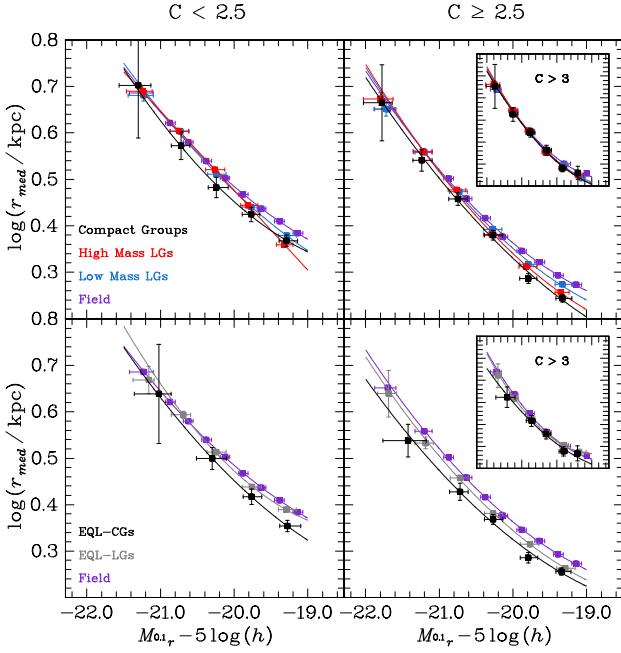


Fig. 12. The $\log(r_{\text{med}})$ of the size distribution as a function of absolute magnitude for late-type galaxies (*left panels*) and early-types galaxies (*right panels*). The abscissas are the median and the horizontal error bars are the 25 and 75 % quartiles of the absolute magnitude distribution within each luminosity bin. Vertical error bars are the 1σ error estimates from the fitting procedure. Continuous lines are the best-fitting quadratic models. *Inset panels* show the results of using $C > 3$ to define early-type galaxies.

lar total luminosity distribution than that of CGs. Since the original samples of CGs and LGs have different redshift distributions, we constructed the LGs group samples by using a Monte Carlo algorithm which randomly selects groups in order to reproduce the redshift distribution of CGs. Similarly, our sample of field galaxies was drawn to reproduce the redshift distribution of CG members. The final samples have 846, 2,536, 2,529 of compact, low-mass, high-mass and equal luminosity loose groups respectively. The corresponding number of member galaxies are: 2,270, 8,749 and 10,055. The equal luminosity subsamples of compact and loose groups include 571 and 2,345 objects, adding up to 1,729 and 10,554 galaxies respectively. The field sample comprises 250,725 galaxies. This statistically significant set of data has been used to compare basic properties of galaxies as well as some photometric scaling relations in different environments.

Our main findings are:

- The properties of galaxies in LGs or in the field do not match those of galaxies in CGs.
- Compact groups are the environment that shows the highest fraction of early-type and red galaxies (our comparison between CGs and field agrees with Lee et al. 2004; Deng et al. 2008; Brasseur et al. 2009). This effect is observed for the whole range of absolute magnitude and stellar mass.
- Galaxies in CGs are, on average, smaller, more compact and have higher surface brightness and stellar mass than in LGs or in the field. Differences are larger when compared to field galaxies and smaller when compared to galaxies in

high mass LGs. This disagrees with previous findings by Deng et al. (2008), but it should be kept in mind they explore a narrower range in luminosity.

- The luminosity function of galaxies in CGs has a characteristic magnitude comparable to that of the most massive LGs, while its faint end slope is similar to that of LGs of intermediate mass (LG luminosity functions measurements by ZM11). These parameters might be indicating that the compact group environment is effective in producing bright galaxies and, at the same time, is a more hostile environment for fainter galaxies compared to LGs. Nevertheless, solid conclusions on this will be obtained when mass measurements of CGs allow a more detailed study of their LF and its dependence on mass.
- The mean colour of CG galaxies is consistent with that of galaxies in high mass LGs over the whole range of absolute magnitudes we probe.
- For a fixed luminosity and over the whole range of absolute magnitudes, both, late and early-type galaxies in CGs are smaller than in EQL groups and in the field. A similar trend is observed when compared to galaxies in low mass groups, although it is not statistically significant. If early-type galaxies are selected using $C > 3$, the corresponding size-luminosity relations are environment independent, in agreement with Weinmann et al. (2009), Nair et al. (2010) and Maltby et al. (2010).

It should be taken into account that we have excluded from our analyses galaxies with r_{50} below the average seeing in SDSS images. While this avoids introducing systematics due to the seeing, it also excludes increasingly larger galaxies as we go from the smallest to the largest redshift considered in this work. Thus the actual differences between galaxies in the different environments probed here might be more significant.

Our results do not significantly change if we: (i) consider only galaxies with spectroscopic redshift in CGs; (ii) restrict our analyses to CGs with higher values of surface brightness. We refer the reader to Appendix A below.

One of our most important results is the excess of galaxies in CGs that are more compact, redder and have higher surface brightness with respect to their LG or field counterparts. These galaxies could be the descendants of galaxies that inhabited LGs before going through a phase of CG. In the CG environment, galaxies have undergone mergers and tidal effects caused by the high densities and low velocity dispersions that characterise CGs. This is in agreement with the large number of CGs that show clear evidences of disturbed morphology (e.g. Mendes de Oliveira & Hickson 1994). The high fraction of red galaxies suggests that this is an efficient process ending in objects with earlier morphological types. This high fraction of red galaxies in CGs also evidence an advanced stage of the morphological transformation processes, consistent with predictions using numerical simulations, see for instance Brasseur et al. (2009), who conclude that galaxies in CGs should be mainly red and dead ellipticals. Our results are also consistent with studies of SFR in compact groups, such as Walker et al. (2010) and Tzanavaris et al. (2010). The differences between the luminosity function of galaxies in CGs and LGs also support this scenario where low luminosity galaxies merge efficiently producing both a lower number of faint galaxies and higher number of bright early-type galaxies as observed.

Recent results (e.g. Cortese et al. 2006; Wilman et al. 2009, McGee et al. (2009) suggest that groups of galaxies play a fundamental role in the pre-processing of galaxies before they be-

come part of more massive systems like clusters of galaxies. Our results indicate that galaxies that inhabit a high density environment, like that of the CGs, have undergone a major transformation than those objects that just went through a phase of LG. Within this scenario, the properties of galaxies in high mass systems like clusters, should show cosmic variations in the galaxy properties depending on the fraction of members that went through a phase of CG.

Appendix A: The Compact Groups Sample: Contamination

As explained in Sect. 2, we consider in this work a subsample of the Catalogue A of CGs identified by McConnachie et al. (2009), limited to the redshift range of $0.06 \leq z \leq 0.18$ and apparent magnitudes $14.5 \leq r \leq 17.77$ (2,270 galaxies). McConnachie et al. (2009) identified CGs following the criteria of Hickson (1982). In particular, the group surface brightness in the r -band is $\mu \leq 26.0$ mag. arcsec⁻². Defined in this way, 1,310 galaxies (~ 58%) have spectroscopic redshift. Fig. A.1 compares the normalised distributions of galaxy parameters for all galaxies in CGs and for those with measured spectroscopic redshift alone. No significant nor systematic differences can be observed.

McConnachie et al. (2008) found that selecting CGs with a higher surface brightness threshold, the contamination rate decreases. In McConnachie et al. (2009) it is stated that the level of contamination is negligible for their Catalogue A. We checked whether our results are affected by contamination by selecting groups with $\mu \leq 25.0$ mag. arcsec⁻² and $\mu \leq 24.0$ mag. arcsec⁻² and then comparing the properties of their galaxies with the members of groups with $\mu \leq 26.0$ mag. arcsec⁻². We show the comparison between the galaxy properties of groups selected according to these three μ values in Fig. A.2. Although galaxy properties of CGs seem similar when we consider CGs selected with different groups surface brightness, CGs with $\mu \leq 24.0$ mag. arcsec⁻² have a higher fraction of early- and red galaxies.

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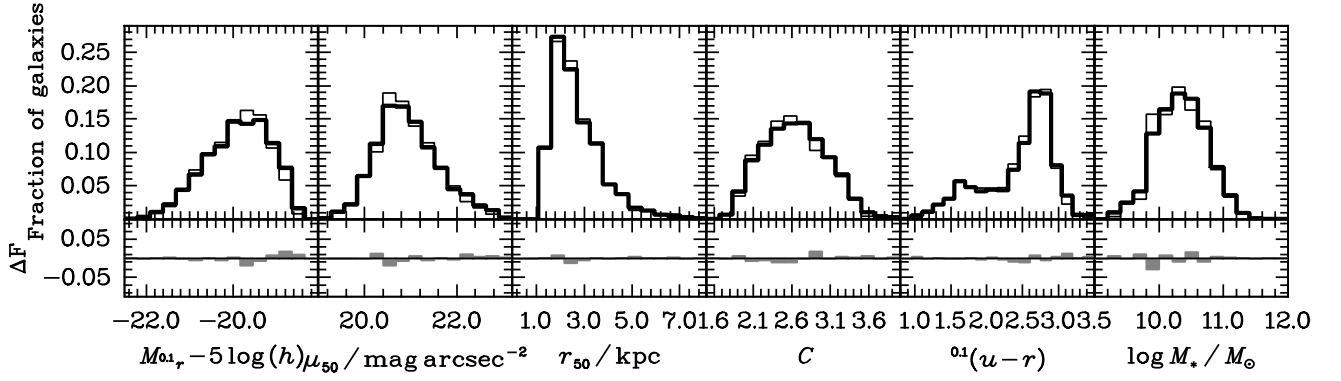


Fig. A.1. Distributions of galaxy properties of CGs: whole sample (*thick line*) and member with spectroscopic redshift (*thin line*).

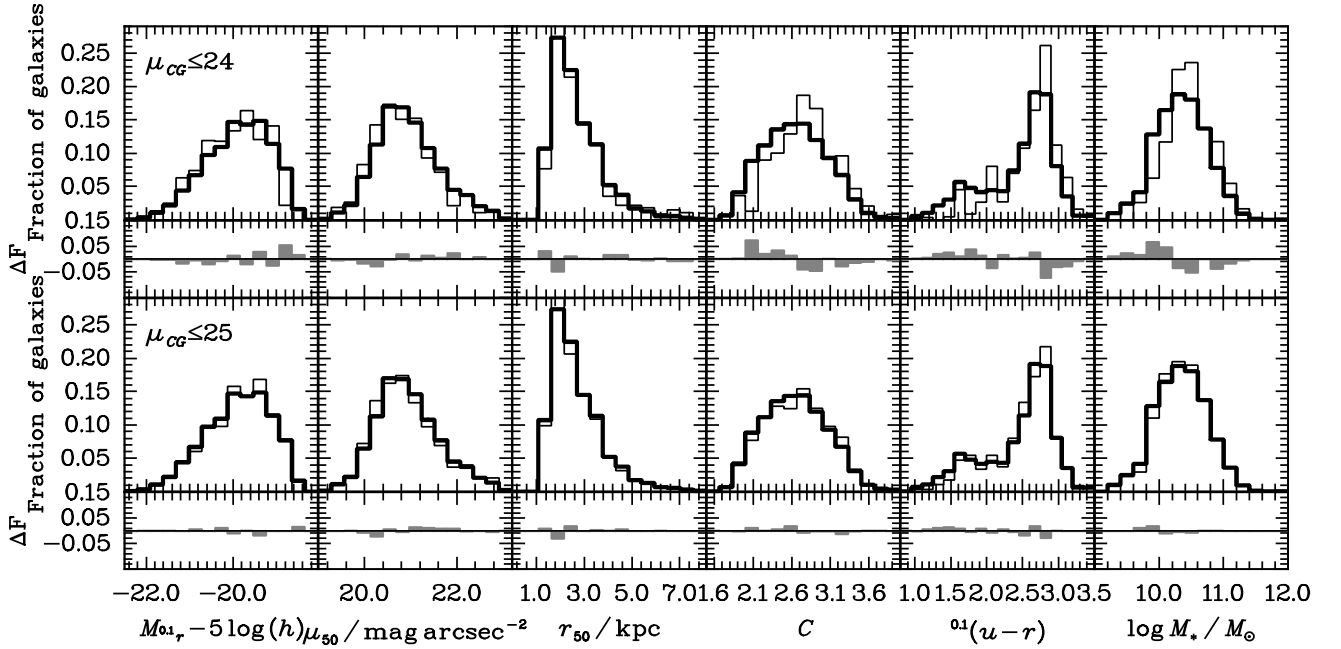


Fig. A.2. Distributions of galaxy properties of CGs with $\mu \leq 26.0$ mag. arcsec $^{-2}$ (*thick line*), $\mu \leq 25.0$ mag. arcsec $^{-2}$ and $\mu \leq 24.0$ mag. arcsec $^{-2}$ (*thin line*).

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